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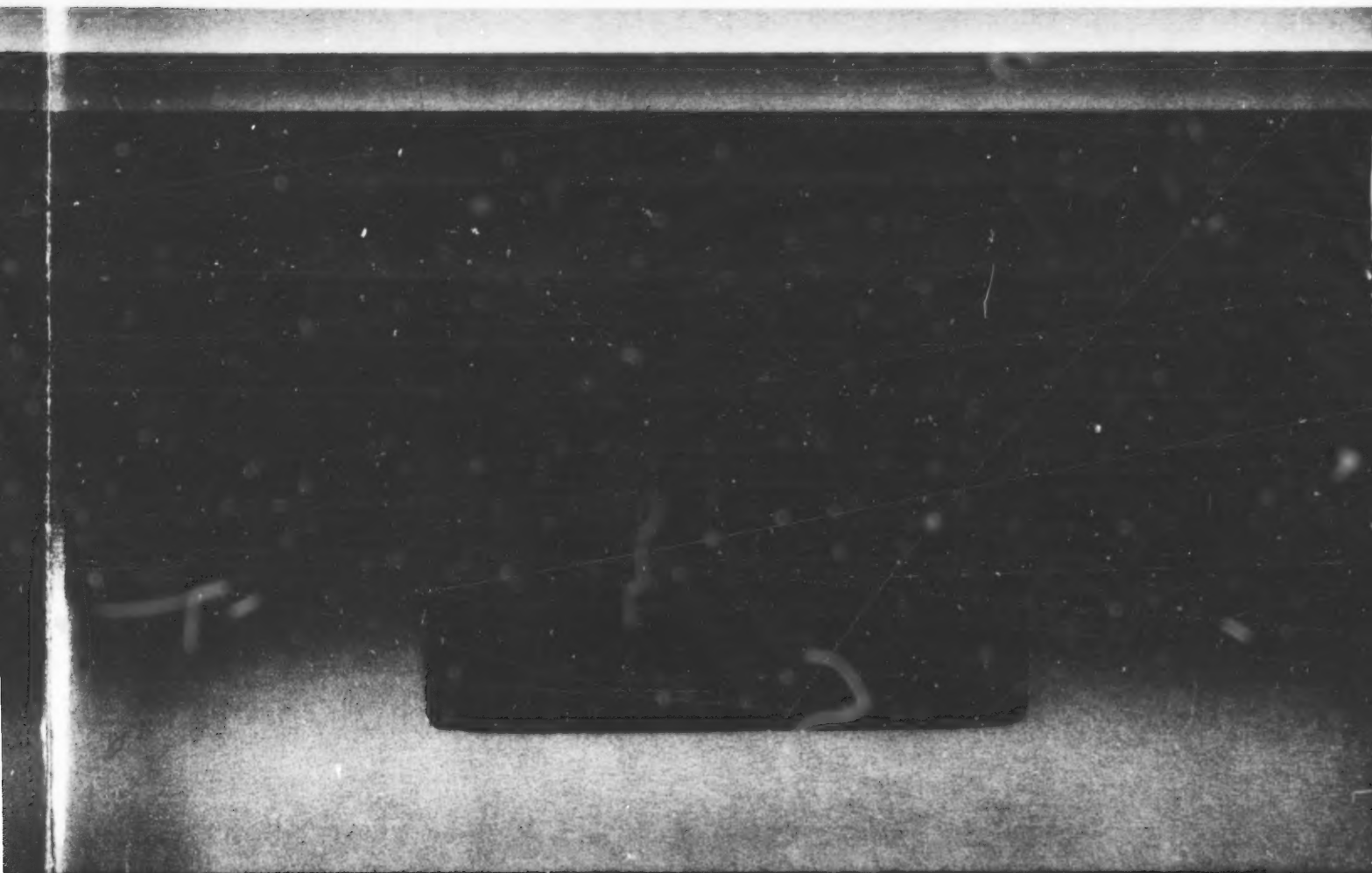

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AN ANALYSIS OF FLOW DATA FROM SENTINEL CREEK, BRITISH COLUMBIA

PART 1

(Unpublished Report)

Contribution No. 87012

December 1986

90-05376/

MANAGEMENT PERSPECTIVE

In 1964, the Government of Canada identified five glacier basins in western Canada for intensive study during the ten-year period of the International Hydrological Decade (IHD). Initial studies of the hydrological data collected at Sentinel Glacier indicated that the length of record was not sufficient for frequency analysis. This report now presents an analysis and assessment of Sentinel Glacier run-off data collected over a period of 18 years. Although the record is still too short to provide conclusive results, plotting positions, empirical probabilities, return periods and ranked flows have been calculated and missing values have been estimated using elementary statistical methods. Two tests, the Log Pearson Type III (LP-III) and the Wakeby distribution, provide good descriptions of the annual maxima of daily flows. For the July total monthly flows, the LP-III distribution provided the best fit and for August flows, the Three Log-Normal distribution was best. The report concludes that an analysis of glacier run-off, based on annual precipitation and melting degree-days, should be undertaken because noise from surrounding basins and other run-off sources is not sufficiently large to mask the main effect.

The techniques successfully applied here could be considered for the analysis of other IHD glacio-hydrological data to determine the downstream effects of run-off.

PERSPECTIVE DE GESTION

En 1964, le gouvernement du Canada choisissait cinq bassins de glaciers dans l'ouest du Canada qui devaient faire l'objet d'études intensives pendant la durée de la Décennie hydrologique internationale (DHI). Des études préliminaires des données hydrologiques provenant du glacier Sentinel indiquaient qu'on ne possédait pas de données pour une période suffisamment longue pour pouvoir procéder à une analyse de fréquence. Ce rapport présente une analyse et une estimation des données sur l'écoulement provenant du glacier Sentinel pendant une période de 18 ans. Bien que cette période soit encore trop courte pour donner des résultats concluants, on a calculé le pointage de positions, les probabilités empiriques, les périodes de récurrence et le classement des écoulements, et estimé les valeurs manquantes en faisant appel à des méthodes statistiques élémentaires. Deux tests, les distributions log Pearson de type III (LP-III) et de Wakeby, donnent de bonnes estimations des maxima annuels des écoulements quotidiens. La distribution LP-III fournissait les meilleurs résultats pour les écoulements mensuels totaux pour juillet, tandis que la distribution lognormale à trois paramètres fournissait de bonnes estimations pour les écoulements en août. Les conclusions du rapport étaient qu'il faudrait entreprendre une analyse de l'écoulement du glacier basée sur la précipitation annuelle et les degrés-jours de fonte, parce que le "bruit" des bassins voisins et d'autres sources d'écoulement n'était pas suffisamment important pour masquer l'effet principal.

Les techniques qui ont été appliquées avec succès ici pourraient être utilisées pour l'analyse d'autres données glacio-hydrologiques de la DHI afin de déterminer les effets de l'écoulement en aval.

ABSTRACT

This report analyses and assesses Sentinel Glacier run-off data collected during and after the international Hydrological Decade (IHD) program, over a period of 18 years. As the hydrological analysis had to be limited to complete data series, only the annual maxima of daily flows, the total monthly and the total annual flows were analysed. The data were determined to be independent samples, randomly selected from a homogeneous population without trend and hence suitable for frequency analysis. The plotting positions, empirical probabilities, return periods and ranked flows were calculated. Missing values have been estimated using elementary statistical methods. The annual maxima, and the total July and August monthly flows were re-estimated and described using four types of distribution function. Of these two, the Log Pearson Type III (LP-III) and the Wakeby distributions, provided good descriptions of the annual maxima of daily flows. The LP-III distribution provided the best fit for the July total monthly flows and the Three Log-normal distribution was best for the August flows. The probability of return periods for various flow conditions has been determined. It is concluded that noise from surrounding basins and other run-off sources is not sufficiently large to negate the utility of an analysis of glacier run-off, based on annual precipitation and melting degree-days.

RÉSUMÉ

Ce rapport analyse et évalue les données sur l'écoulement provenant du glacier Sentinel pendant et aprés le programme de la Décennie hydrologique internationale (DHI), sur une période de 18 ans. Étant donné que l'analyse hydrologique devait se limiter à des séries de données complètes, seuls ont été analysés les maxima annuels des écoulements quotidiens, les écoulements mensuels totaux et les écoulements annuels totaux. On a déterminé que les données étaient des échantillons indépendants, choisis aux hasards dans une population homogène sans tendance et convenant donc à l'analyse de fréquence. Les positions de pointage, les probabilités empiriques, les périodes de récurrence et le classement des écoulements ont été calculés. Les valeurs manquantes ont été estimées à l'aide de méthodes statistiques élémentaires. On a réévalué et décrit les maxima annuels et les écoulements mensuels totaux pour juillet et août à l'aide de quatre types de distribution. Deux de ces méthodes, la distribution log Pearson de type III (LP-III) et la distribution de Wakeby, ont fourni de bonnes estimations des maxima annuels des écoulements quotidiens. La distribution LP-III donnait les meilleurs résultats pour les écoulements mensuels totaux de juillet et la distribution lognormale à trois paramètres fournissait les meilleures estimations pour les écoulements en août. On a déterminé la probabilité de périodes de récurrence des diverses conditions d'écoulement. On en a conclu que le "bruit" des bassins voisins et d'autres sources d'écoulement n'était pas suffisamment important pour rendre inutile une analyse de écoulement provenant du glacier basée sur la précipitation annuelle et les degrés-jours de fonte.

CONTENTS

Abstract 1

Introduction 2

Observation and Data Evaluation 3

Analysis of the Annual Maxima of Daily Flows 6

Analysis of the July and August Monthly Total Flows 10

Conclusions 13

Acknowledgments 16

References 17

TABLES

1 Sentinel Creek Monthly Total Flows, dam^3 May - October, 1966 - 1983 18

2 Annual Maxima of Daily Flows, dam^3 19

3 Plotting Positions of the Annual Maxima of Daily Flows 20

4 Frequency Analysis - Generalized Extreme Value Distribution 21

5 Frequency Analysis - Three-Parameter Lognormal Distribution 22

6 Frequency Analysis - Log Pearson Type III Distribution 23

7 Frequency Analysis - Wakeby Distribution 24

8 Comparison of the Flow Estimates Obtained from Various Frequency Distributions for the Annual Maxima of Daily Flows in $dam^3\ Day^{-1}$, 1966 - 1983 25

9 Plotting Positions of the Total July Monthly Flows 26

10 Plotting Positions of the Total August Monthly Flows 27

11 Comparison of the Flow Estimates by Various Frequency Distributions for the July and August Total Monthly Flows in $dam^3\ Month^{-1}$, 1966 - 1983 28

ILLUSTRATIONS

1 Location of Sentinel Glacier 29

2 Maximum, Minimum and Mean Total Monthly Flows from Sentinel Glacier, B.C., May - October, 1966 - 1983 30

3 Total Annual Flows from Sentinel Glacier, B.C., 1966 - 1983 31

4 Percentage Contribution of Each Month to the Total Annual Flows, Sentinel Glacier, B.C ., May - October, 1966 - 1983 32

5 Lognormal Plotting Positions of the Annual Maxima of Daily Flows, 1966 - 1983 33

6 Generalized Extreme Value Distribution of the Annual Maxima of Daily Flows, 1966 - 1983 34

7 Three-Parameter Lognormal Distribution of the Annual Maxima of Daily Flows, 1966 - 1983 34

8 Log Pearson Type III Distribution of the Annual Maxima of Daily Flows, 1966 - 1983 35

9 Wakeby Distribution of the Annual Maxima of Daily Flows, 1966 -1983 35

10 Lognormal Plotting Positions of the Total July Flows, 1966 - 1983 36

11 Generalized Extreme Value Distribution of the Total July Flows, 1966 - 1983 37

12 Three-Parameter Lognormal Distribution of the Total July Flows, 1966 - 1983 37

13 Log Pearson Type III Distribution of the Total July Flows, 1966 - 1983 38

14 Wakeby Distribution of the Total July Flows, 1966 - 1983 38

15 Deviations of the Estimated Flows from Actual Values of the Total July Flows, 1966 - 1983 39

16 Lognormal Plotting Positions of the Total August Flows, 1966 - 1983 40

17 Generalized Extreme Value Distribution of the Total August Flows, 1966 - 1983 41

18 Three-Parameter Lognormal Distribution of the Total August Flows, 1966 - 1983 41

19 Log Pearson Type III Distribution of the Total August Flows, 1966 - 1983 42

20 Wakeby Distribution of the Total August Flows, 1966 - 1983 ... 42

21 Deviations of the Estimated Flows from Actual Values of the Total August Flows, 1966 - 1983 43

INTRODUCTION

Sentinel Creek is the meltwater channel from Sentinel Glacier (lat. 49°54', long. 122°59'W) accepting some additional waters from slopes and snowpatches along its route. The basin is surrounded by several prominent peaks and ridges. The creek is approximately 2 km long and drains into Garibaldi Lak (elevation 1478 m a.s.l.). Sentinel Glacier basin descending from the Glacier Pikes at an elevation of 2158 m a.s.l., lies on the northeast side of Garibaldi Névé, in Garibaldi Provincial Park, 70 km north of Vancouver. The 5 km^2 basin faces north and has approximately 1.8 km^2 under glacier-ice cover. The stream gauge is about 700 m upstream from the lake at an elevation of 1500 m.

During the International Hydrologic Decade (IHD, 1964 - 1974), data were collected on representative glaciers around the world. Canada's commitment included studies of Arctic and Cordilleran glaciers, one of which was Sentinel Glacier in the southern Coast Mountains, B.C. During the ten-year period of the IHD, glacier mass balance, climatological and hydrological data were collected on Sentinel Glacier, (Figure 1), processed and analysed. However, as pointed out by Klemes (1986 a, b) the short period of record could not provide a sample size that would permit frequency analyses of Sentinel Creek flow data .

After the IHD program ended, studies continued on Sentinel Glacier and more data were collected. Thus, it became possible to attempt the

analysis of flow data for a longer period i.e. from 1966 to 1983 and to complement studies previously done under the IHD program. Even so, because of the relatively short length of record, conclusions are still tentative and the excercise should be repeated as additional data become available. Two types of flow data will be analysed: the annual maxima of daily flows and the total monthly flows for July and August, because these records are complete.

The second part of this report will show what is the effect of Sentinel Glacier on discharge, compared to flows from nearby unglacerized basins. Therefore, the conclusions to be derived from the Sentinel Creek flows will be applied to adjacent unglacierized areas.

OBSERVATIONS AND DATA EVALUATION

Stream flow measurements began in 1966 at the gauging site below the confluence of the two main channels collecting meltwater from Sentinel Glacier and the adjacent slopes. Measurements were made annually using a Gurley meter and the salt-dilution technique during the International Hydrological Decade. The salt-dilution method was discontinued after three years because of the similarity of results using the two measuring methods. The Water Survey of Canada constructed a gauging station and conducted its own measurements with the Gurley current meter until 1984 when the station was inundated by an October flood. Water levels were monitored using a Stevens A-35 automatic stage recorder. On the basis of discharge measurements, a rating curve was derived by the Water Survey of

Canada and the glaciological crew. Measurable run-off begins on Sentinel Creek during the second part of May, and usually ends in late October. During June, July, August and September the 5 square kilometre drainage area is able to produce continuous flows. Discharge data for some of the June, September and October months are not complete and some of the May data are missing entirely.

Normal hydrologic analysis procedure prohibits the use of incomplete monthly data but in practice the incomplete data set can reasonably be "supplemented" before any statistical analysis is done . However, the estimated data leads to results that must be used with caution. To complete the sample size, certain manipulations with the flow data were carried out. Estimates were based on daily flows plotted against time with missing values filled in the time series diagram only when identical weather conditions prevailed prior to and after the dates of the missing data. The interpolated individual daily values were always lower than the monthly maximum daily flows. Therefore, the estimated values do not influence the position and the magnitude of the maximum daily flow values. When the data base for the total monthly flows were compiled, some of the May and October flow values were estimated using daily means of the monthly flows (Figure 2). This figure shows the minimum, maximum and the mean position of the monthly total flows for the 18-year period. The total monthly July flows provided the highest values, followed by June, August, September and October. On this diagram, zero values were assumed for the April and November monthly total flows. The actual and estimated flow values for each of the six months of the 18-year period are shown in Table 1. The table also shows the annual (six month) totals

which average 15,554 dam^3* over the 18 year period. This corresponds to a depth of 3.1 m of water over the basin. June appears to be the most variable month although July provides the highest contribution to the annual total flow. Table 1 and Figure 2 indicate that variation during May is the least significant, ranked after October. The reliability of the flow data for May and October is questionable because of extensive extrapolation of the daily values.

The plot of the total annual flows versus time is shown in Figure 3. In 1967 the total annual flow was abnormally high. The second highest value was reached in 1978. These high values were probably due to exceptionally high rainfalls in addition to run-off produced by normal melting processes.

The details of the monthly structure of total flows are given in Figure 4. This shows that June, July, August and September produced high flow values. The contribution during these months to the total annual flow was significant. The composite diagram breaks down the monthly percentage contribution for each year. However, the individual monthly contributions are omitted and the isolines suggest the pattern only. According to this figure, there is a strong ridge over July which extends slightly over August. However, it is not continuous. Five troughs appear in the pattern, namely in 1967, 1969, 1975/76 and from 1978 onwards. This

* dam^3, cubic dekameter (1000 m^3), is a unit of volume. 1 dam^3 divided by a drainage area of 1 km^2 gives a depth of run-off from the basin of 1mm.

diagram basically confirms the conclusions drawn from Figure 2 and 3. Despite the troughs in the isopleth pattern, 1967 exceeded the highest amount of annual flow, because every month contributed equally throughout the whole summer season to produce the high annual total flow. The column totals in Figure 4 indicate that flows in June, July, August, September contributed each year to the total annual flow by as much as 86 to 95%. Due to uncertainty of the estimated flow data for May and October, it appears justifiable to conclude that flows in June, July, August and September are the major contributors to the total annual flow.

Less scrutiny is required to examine the reliability of the annual maxima of daily flows, since they are true measured values. The greatest problem is due to the fact that only 18 values were available for the analysis. As a result conclusions based on the 18 years of data are doubtful.

ANALYSIS OF THE ANNUAL MAXIMA OF DAILY FLOWS

Frequency analysis can assist in deducing empirical inferences only from those samples that fulfill the elementary criteria of statistical analysis. That is, the individual members of the sample must be randomly selected, the successive values of the series must be independent from each other without a trend, and the values must be taken from a single homogeneous population.

The criteria used for testing the annual maxima of daily runoff values are those described by Pilon et. al (1985). Accordingly, the annual maximum values of Table 2 were subjected to a Spearman test for independence. At the 5% level of significance, the data did not display significant serial dependence. The Spearman test for trend did not indicate significant trend at the 5% level. The randomness test showed that the sample was significantly random. The test for homogeneity concluded that the data at the 5% level were drawn from the same population. The estimated non parametric Mann-Whitney U = 37.0 has been found slightly above the tabulated limit of 5% (U tabulated = 21.0). The difference of 165 at 5% level (37-21 = 16) indicates no significant location difference, that is, run-off data were found homogeneous.

The plotting positions, the empirical probabilities, the return periods and the ranked flows of the maximum flows were calculated and are listed in Table 3. Although the table is self explanatory, some remarks about its interpretation could be of benefit. The 18 maxima are listed and ranked from 1 to 18. The empirical return periods are computed with the Cunnane distribution formula (Pilon et. al, 1985), as P_i = (m-0.4)/(N+0.2), where P_i is the empirical probability value (column 6), m is the rank of the flows and N is the number of years over which the average probability was calculated. The "Return Period" is given by the number of years in column 7, which is derived as Year = $1/P_i$. To illustrate the interpretation of Table 3, the ranked flow #7 has been selected as an example. In row 7 and column 6 there is a 36.26% chance that the 322.3 dam^3 flow will be reached or exceeded each year. The

"2.758 Years" means that this is almost 2.8 average number of "Year" during which the given flow value of 322.3 dam^3 will be equalled or exceeded at least once. This flow value may in fact appear several times in a 2.8 year period. The "Return Period Year" values may occur over a long period of time, perhaps a 1000 years or so.

The sample statistics of the maximum flow values of the frequency analysis are calculated according to the techniques and descriptions given by Pilon et. al (1985) and listed in Table 4. It can be seen from this table that the coefficient of skewness (C.S. = 1.165) is positively skewed and far from zero which is the ideal value for normal and lognormal distributions. The coefficient of kurtosis (C.K. = 4.945) is more than the ideal value of 3. However, the lognormal skewness is 0.5 and the lognormal kurtosis is 3.4 which are close to the ideal values. The coefficient of variation (C.V., a parameter which is, as opposed to standard deviation, independent of the scale used in measuring the variates of the sample) is high, 36% of the mean. The maximum and minimum flow values and the lower and upper outlier limits of the flow data are also listed in the upper parts of the Sample Statistics tables (tables 4 - 7).

The plotting positions of the individual flows from Table 3 were transferred to Figure 5. In this diagram the normal probability distribution is shown in a straight line and the scatter of the actual flows indicate the degree of deviation of the real values from normality. To find the best distribution model for the annual maxima of the daily flows, four different distribution types were tested on the available flow

values, such as:

i) Generalized Extreme Value Distribution (GEV),

ii) Three-Parameter Lognormal Distribution (3-PLN),

iii) Log Pearson Type III DIstribution (LP-III), and

iv) Wakeby Distribution.

The theories for these distributions are described by Sangal (1986) and Pilon et.al (1985). The results of the calculation are given in Tables 4 to 7. The plots for the distributions with the scatter of the real flow values are shown in Figures 5 to 9.

The ensuing discussion is restricted only to a brief explanation that should enable the reader to appreciate the calculated results (Tables 4 to 7). GEV is a 3-parameter distribution with parameters U, A and K (Table 4). U is a location parameter, A a scale parameter and K a shape parameter. 3-PLN distribution is a distribution in which the log of the variable (X-A) is normally distributed; where the X variate is a random variable, A is a parameter and (X-A) is the reduced variable. In this distribution, the log of any linear function of X is normally distributed. Thus, the function, $y=\ln(X-A)$, is also normally distributed. The variate X is bounded below by the parameter A. The flood frequency regime section of Table 5 has been calculated with the parameters: A, M and S which are computed with the moments (Pilon et.al, 1985). LP-111 distribution has 3 parameters: A, B and M; where A represents the scale factor, B the shape parameter and M a boundary parameter (Table 6).

Wakeby distribution is a 5-parameter distribution. These parameters are M, A, B, C and D. Where A and C are scale, B and D shape and M the location parameter. The advantage of this distribution function is that it can assume various shapes, such as an "S" or "hockey stick" form. Parameters A and B can resemble lower flows (left-hand tail), while parameters C and D can control the higher flows (right-hand tail) of the distribution. If the parameter D is positive then the distribution has no upper boundary at M; and this is exactly the case in Table 7.

A visual inspection of the five scatter diagrams (Figure 5 to 9) reveals that the best fit is probably obtained with LP-III and the Wakeby distribution models. The GEV and the 3-PLN distributions appear to give a poorer fit than the ordinary lognormal distribution model in Figure 5. A comparative summary of the various frequency distribution results is given in Table 8. The estimates of the four distributions are similar between the 10% and 99% probability bounds (shown with shaded area). The divergence of the various estimates at higher return periods is quite significant. The estimated flow values which are close to actual flows are circled in Table 8. At the high flow regime, the GEV and the 3-PLN distributions give higher estimates than the Wakeby and the LP-III distributions. The uncertain estimates for the higher return period suggest that a frequency analysis based only on 18 summer observations cannot be extended beyond the 10-year return period with confidence.

ANALYSIS OF THE JULY AND AUGUST MONTHLY TOTAL FLOWS

A descriptive presentation of the monthly and annual total flows has been attempted in the chapter on Observations and Data Evaluation. Attention is given to the July and August total flows. Figure 4 revealed that July and August contributed to the total annual flow by 55%. This high contribution rate indicates that it may be sufficient to analyse high flows for only these two months because of a flood risk that may occur during this period.

The analysis of the July and August monthly totals are similar to the analysis of the maximum daily flows. The monthly total flow values are listed in Table 1. The prerequisite statistical tests were similarly performed on these two monthly values for independence, randomness, trend and homogeneity (Thom, H.C.S., 1966). As a result, the July and August total flows were found independent samples and randomly selected from a homogenous population without trend. The ranked plotting positions for July and August are listed in Table 9, 10 and their respective plots are shown in Figure 10 and 16. The best fit curves of the four distribution functions are shown for July in Figure 11 to 14 and for August in Figure 17 to 20.

The straight line of the July lognormal distribution (Figure 10) provides a better fit in the medium flow domain that in the lower and upper regime. The GEV (Figure 11) and the LP-III (Figure 13) July estimates

appear to give better fit in the high flow regime than the other two distribution functions (Figure 12, 14). When discussing the annual maxima of daily flows, the frequency analysis tables were presented individually for each type of distribution (Table 4 to 7) and the four estimates were summarized in a single table (Table 8). Whereas, the frequency analysis of the July (and also August) monthly totals are shown in one table only (Table 11). In this table the best fit estimates are also circled and the shaded areas indicate values that are quantitatively close to the measured values. On the basis of the shaded values, it appears, that the longest acceptable return period cannot be more than 10 years. Deviations of the best fit estimates from the actual July flow values were calculated for each of the four distributions and are shown in Figure 15. The abscissa of this figure indicates ranked flow values from 1 to 18 (that is, from low to high flows). The ordinates show the deviations of the samples from the actual ranked flows. Real flow is represented by the zero deviation which is the horizontal abscissa line in each diagram. The average of the July monthly total flows amounts to 4359 dam^3 and the standard deviation of the real flows is 792.8 dam^3. The one standard deviation has never exceeded the best fit estimates. The deviation patterns caused by the four distribution estimates are in similar phase, their magnitude is however, different. The absolute values of the deviations, ranging from 170.5 dam^3 to 184.3 dam^3, are less than or equal to 4% of the 18-year mean of the July flows. These estimates for July are considered reasonable because the deviations never exceeded 23% of the standard deviation.

The lognormal plot of the August total flows is shown in Figure 16 and the frequency analysis diagrams are presented in Figures 17 to 20. Estimates of the four distribution functions are combined in one table (Table 11). Reasonable estimates appear only in the low flow regime of the August flows. Only the 3-PLN distribution function can estimate a qualitatively acceptable 10-year return period. Deviations of the estimated from the real flows for the 18 August records (Figure 21) are less than those found for the July total flows. The best fit was obtained with the 3-PLN distribution and the worst with the LP-111 distribution. Deviations ranged from 2.1% to 3.8% of the 18-year mean of the August flows. The average of the August total flows reached 4047 dam^3 and the standard deviation of the flows is 649.4 dam^3. Given the fact that the August deviations ranged from 15% to 23% of the standard deviation, the August total flow estimates can also be considered reasonable.

CONCLUSIONS

As shown earlier, flow gauge measurements were conducted about 1300 m downstream from Sentinel Glacier on Sentinel Creek which picks up not only glacier run-off but also snowmelt run-off from the unglaciated adjacent slopes. The demonstrated statistical tests did not reveal non-homogeneity in any of the flow data sets. Homogeneity statistics indicated that the measured stream flow was produced by only one physical process, the glacier snowmelt process. However, the additional input of snowmelt from adjacent slopes and random precipitation might cause some noise and

deviation from the estimates. The estimates might be imperfect not only because of the additional flows from nearby slopes but because of the short observation period as well. However, statistical homogeneity suggests that the noises created by tributaries from unglaciated slopes are not significant. Therefore, an attempt will be made to compare the glacier run-off with discharge from unglaciated basins by means of annual precipitation and the accumulated annual melting degree days. This will be reported on in Part 2.

The comparative summaries of the four frequency distributions for the annual maxima of daily flows and the total July and August flows suggested that the return period estimates could not be extended beyond 10 years with confidence. For the annual maximum flows it has also been found that all four distributions were similar within 10-90% probability bounds. In other words, estimates of the low and high flow regimes of the annual maximum flows were less accurate than those of the middle flow regimes. For all the four distributions, the July total monthly estimates were higher than the actual values being overestimated by as much as 4%. However, the August total flows were in general well estimated, especially with the 3-PLN distribution function. The 3-PLN estimates deviated from the 18- year mean of the August total flows only by 2.1%.

Much of the data produced by the glacier-hydrological studies conducted during the IHD program have not been fully analysed. This analysis is a contribution to that end. Previously, two run-off forecasting studies were undertaken for Sentinel Glacier by Cohen, 1981 and Cohen et al., 1982

using only 1971 and 1972 runoff values. A good statistical assessment of the flow conditions from Sentinel Glacier will improve our ability to determine the effect of the glacier on discharge, as opposed to flows from nearby unglacierized basins. The authors recommend continuation of the stream-guage measurements not only at Sentinel Creek but the extension of the observations downstream in the valley and the collection of discharge data from adjacent unglacierized areas in a similar climate setting. It is also recommended that the analysis be updated as additional data become available. These flows and their return periods do not only have glaciological significance for they are also essential input data for future hydrologic designs and environment protection projects in this region. We would particularly like to draw attention to the fact that discharge from the Garibaldi Lake flows across a zone which is spotted with ongoing landslides. (Moore and Mathews, 1978).

A correlation and regression of the total annual flows against the total annual precipitation and accumulated melting degree-days will be included in Part 2 of this study. Flows from adjacent unglaciated basins will be compared with the same climatological data to clarify effect of Sentinel Glacier on run-off.

ACKNOWLEDGMENTS

The authors would like to thank G. Holdsworth, W. Nickolaichuck, C.S.L. Ommanney, National Hydrology Research Institute and F. Morton formerly of National Hydrology Research Institute, Inland Waters Directorate, Environment Canada, for their valuable comments.

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TABLE 1: Sentinel Creek Monthly Total Flows, dam^3
May - October
1966-1983

YEAR	MONTHS						ANNUAL TOTAL
	May	June	July	August	September	October	
1966	414*	3010	3756	3765	2513	769	14,227
1967	414*	5364	5387	5051	4159	1815	22,190
1968	180	2844	5355	3495	2573	777	15,224
1969	662	3908	3714	3318	3180	225	15,007
1970	522	3507	3612	3332	1574	780	13,027
1971	414*	2032	4423	5116	2361	790	15,136
1972	414*	3969	5496	4352	1445	770	16,446
1973	541	2682	4368	3423	2187	760	13,961
1974	414*	2557	5893	4965	1317	300	15,446
1975	560	3007	4024	3261	1695	1177*	13,724
1976	550	3000	4131	3965	3006	1177*	15,829
1977	414*	2452	2494	4611	2424	1177*	13,572
1978	560	3846	5118	4691	3451	1172	18,838
1979	550	2878	3873	4220	3670	1170	16,361
1980	414*	3000	4125	3839	2871	1177*	15,426
1981	560	2916	3637	4261	2736	1482	15,592
1982	550	3010	4511	3160	2547	1691	15,469
1983	414*	3107	4088	4016	1917	965	14,507
AVE.	475	3155	4334	4047	2535	1010	15,554

* = estimated values

TABLE 2: Annual Maxima of the Daily Flows, dam^3

SEQ. NO.	YEAR	MON	FLOW
1	1966	9	187
2	1967	9	260
3	1968	7	454
4	1969	8	276
5	1970	6	200
6	1971	8	367
7	1972	7	590
8	1973	7	203
9	1974	7	389
10	1975	8	267
11	1976	9	311
12	1977	9	218
13	1978	9	391
14	1979	9	370
15	1980	9	226
16	1981	9	209
17	1982	10	322
18	1983	9	195

TABLE 3: Plotting Positions of the Annual Maxima of the Daily Flows.

Annual Maxima of the Daily Flows

MONTH (1)	YEAR (2)	DATA (3) (CMS)	ORDERED (4) (CMS)	RANK (5)	PROB. (6) (%)	RET. PERIOD (7) (YEARS)
Sept	1966	187.0	589.7	1	3.30	30.333
Sept	1967	259.6	454.0	2	8.79	11.375
July	1968	454.0	391.4	3	14.29	7.000
August	1969	276.5	389.0	4	19.78	5.056
June	1970	200.0	369.8	5	25.27	3.957
August	1971	367.0	367.0	6	30.77	3.250
July	1972	203.5	322.3	7	36.26	2.758
July	1973	589.7	311.0	8	41.76	2.395
July	1974	389.0	276.5	9	47.25	2.116
August	1975	267.0	267.0	10	52.75	1.896
September	1976	311.0	259.6	11	58.24	1.717
September	1977	217.7	226.4	12	63.74	1.569
September	1978	391.4	217.7	13	69.23	1.444
September	1979	369.8	209.1	14	74.73	1.338
September	1980	226.4	203.5	15	80.22	1.247
September	1981	209.1	200.0	16	85.71	1.167
October	1982	322.3	195.3	17	91.21	1.096
September	1983	195.3	187.0	18	96.70	1.034

TABLE 4: Frequency Analysis - Generalized Extreme Value Distribution.
Annual Maxima of the Daily Flows

SAMPLE STATISTICS

	MEAN	S.D.	C.V.	C.S.	C.K.
X Series	302.017	108.626	0.360	1.165	4.945
LN X Series	5.656	0.334	0.059	0.521	3.040

X(MIN) = 187.000
X(MAX) = 589.700
LOWER OUTLIER LIMIT OF X = 131.192

TOTAL SAMPLE SIZE = 18
No. OF LOW OUTLIERS= 0
NO. OF ZERO FLOWS = 0

SOLUTION OBTAINED VIA MAXIMUM LIKELIHOOD

GEV PARAMETERS: U = 237.11 A = 56.694 K = -0.510

FLOOD FREQUENCY REGIME

RETURN PERIOD	EXCEEDANCE PROBABILITY	FLOOD
1.003	0.997	171.00
1.050	0.952	189.00
1.250	0.800	213.00
2.000	0.500	260.00
5.000	0.200	365.00
10.000	0.100	476.00
20.000	0.050	631.00
50.000	0.020	938.00
100.000	0.010	1290.00
200.000	0.005	1780.00
500.000	0.002	2760.00

TABLE 5: Frequency Analysis - Three-Parameter Lognormal Distribution
Annual Maxima of the Daily Flows

SAMPLE STATISTICS

	MEAN	S.D.	C.V.	C.S.	C.K.
X Series	302.017	108.626	0.360	1.165	4.945
LN X Series	5.656	0.334	0.059	0.521	3.040
LN (X-A) Series	4.355	1.096	0.252	-0.439	2.812

X(MIN) = 187.000
X(MAX) = 589.700
LOWER OUTLIER LIMIT OF X = 131.192

TOTAL SAMPLE SIZE = 18
No. OF LOW OUTLIERS= 0
NO. OF ZERO FLOWS = 0

SOLUTION OBTAINED VIA MAXIMUM LIKELIHOOD

3-LN PARAMETERS: A = 178.444 M = 4.355 S = 1.096

FLOOD FREQUENCY REGIME

RETURN PERIOD	EXCEEDANCE PROBABILITY	FLOOD
1.003	0.997	182.00
1.050	0.952	191.00
1.250	0.800	209.00
2.000	0.500	256.00
5.000	0.200	374.00
10.000	0.100	496.00
20.000	0.050	651.00
50.000	0.020	918.00
100.000	0.010	1180.00
200.000	0.005	1490.00
500.000	0.002	2000.00

TABLE 6: Frequency Analysis - Log Pearson Type III Distribution
Annual Maxima of the Daily Flows

SAMPLE STATISTICS

	MEAN	S.D.	C.V.	C.S.	C.K.
X Series	302.017	108.626	0.360	1.165	4.945
LN X Series	5.656	0.334	0.059	0.521	3.040

X(MIN) = 187.000
X(MAX) = 589.700
LOWER OUTLIER LIMIT OF X = 131.192

TOTAL SAMPLE SIZE = 18
No. OF LOW OUTLIERS= 0
NO. OF ZERO FLOWS = 0

SOLUTION OBTAINED VIA MOMENTS

LP3 PARAMETERS: A = 0.8682E-01 B = 14.76 LOG (M) = 4.374
M = 79.35

FLOOD FREQUENCY REGIME

RETURN PERIOD	EXCEEDANCE PROBABILITY	FLOOD
1.003	0.997	137.00
1.050	0.952	173.00
1.250	0.800	215.00
2.000	0.500	278.00
5.000	0.200	374.00
10.000	0.100	445.00
20.000	0.050	517.00
50.000	0.020	620.00
100.000	0.010	705.00
200.000	0.005	795.00
500.000	0.002	926.00

TABLE 7: Frequency Analysis - Wakeby Distribution
Annual Maxima of the Daily Flows

SAMPLE STATISTICS

	MEAN	S.D.	C.V.	C.S.	C.K.
X Series	302.017	108.626	0.360	1.165	4.945
LN X Series	5.656	0.334	0.059	0.521	3.040

X(MIN) = 187.000
X(MAX) = 589.700
LOWER OUTLIER LIMIT OF X = 131.192

TOTAL SAMPLE SIZE = 18
No. OF LOW OUTLIERS= 0
NO. OF ZERO FLOWS = 0

THE FOLLOWING WAKEBY PARAMETERS WERE OBTAINED BY ASSUMING M TO BE NON-ZERO. THE ITERATION ALGORITHM WAS NOT REQUIRED

M = 159.412 A = 67.810 B = 1.88 C = 1959.310 D = 0.048

FLOOD FREQUENCY REGIME

RETURN PERIOD	EXCEEDANCE PROBABILITY	FLOOD
1.003	0.997	160.00
1.050	0.952	170.00
1.250	0.800	204.00
2.000	0.500	275.00
5.000	0.200	381.00
10.000	0.100	454.00
20.000	0.050	529.00
50.000	0.020	630.00
100.000	0.010	710.00
200.000	0.005	792.00
500.000	0.002	905.00

TABLE 8: Comparison of the Flow Estimates Obtained From Various Frequency Distributions for the Annual Maxima of Daily Flows in $dam^3\ day^{-1}$, 1966 - 1983

Return Period Year	Probability %	DISTRIBUTIONS GEV	3-PLN	LP-111	Wakeby	Actual
1.003	99.7	171	182	137	160	187
1.05	95.2	189	191	173	170	195.3
1.25	80.0	213	209	215	204	203
2.00	50.0	260	256	278	275	267
5.00	20.0	365	374	374	381	389
10.00	10.0	476	496	445	454	454
20.00	5.0	631	651	517	529	589
50.00	2.0	938	918	620	630	
100.00	1.0	1290	1180	705	710	
200.00	.5	1780	1490	795	792	
500.00	.2	2760	2000	926	905	

TABLE 9: Plotting Positions of the Total July Monthly Flows

July Monthly Total

MONTH (1)	YEAR (2)	DATA (3) (CMS)	ORDERED (4) (CMS)	RANK (5)	PROB. (6) (%)	RET. PERIOD (7) (YEARS)
June	1966	3756.0	5892.8	1	3.30	30.333
June	1967	5387.0	5495.6	2	8.79	11.375
July	1968	5354.7	5387.0	3	14.29	7.000
July	1969	3714.5	5354.7	4	19.78	5.056
July	1970	3611.9	5118.3	5	25.27	3.957
July	1971	4423.4	4510.8	6	30.77	3.250
July	1972	5495.6	4423.4	7	36.26	2.758
July	1973	4367.7	4367.7	8	41.76	2.395
July	1974	5892.8	4131.0	9	47.25	2.116
July	1975	4023.6	4124.8	10	52.75	1.896
July	1976	4131.0	4087.8	11	58.24	1.717
July	1977	2943.6	4023.6	12	63.74	1.569
July	1978	5118.3	3873.2	13	69.23	1.444
July	1979	3873.2	3756.0	14	74.73	1.338
July	1980	4124.8	3714.5	15	80.22	1.247
July	1981	3637.0	3637.0	16	85.71	1.167
July	1982	4510.8	3611.9	17	91.21	1.096
July	1983	4087.8	2943.6	18	96.70	1.034

TABLE 10: Plotting Positions of the Total August Monthly Flows

Sentinel August Monthly Totals

MONTH (1)	YEAR (2)	DATA (3) (CMS)	ORDERED (4) (CMS)	RANK (5)	PROB. (6) (%)	RET. PERIOD (7) (YEARS)
August	1966	3765.0	5116.5	1	3.30	30.333
August	1967	5050.8	5050.8	2	8.79	11.375
August	1968	3494.7	4964.7	3	14.29	7.000
August	1969	3318.0	4691.5	4	19.78	5.056
August	1970	3331.8	4611.3	5	25.27	3.957
August	1971	5116.5	4352.1	6	30.77	3.250
August	1972	4352.1	4260.7	7	36.26	2.758
August	1973	3422.8	4219.8	8	41.76	2.395
August	1974	4964.7	4016.2	9	47.25	2.116
August	1975	3260.6	3964.7	10	52.75	1.896
August	1976	3964.7	3838.9	11	58.24	1.717
August	1977	4611.3	3765.0	12	63.74	1.569
August	1978	4691.5	3494.7	13	69.23	1.444
August	1979	4219.8	3422.8	14	74.73	1.338
August	1980	3838.9	3331.8	15	80.22	1.247
August	1981	4260.7	3318.0	16	85.71	1.167
August	1982	3159.6	3260.6	17	91.21	1.096
August	1983	4016.2	3159.6	18	96.70	1.034

TABLE 11: Comparison of the Flow Estimates Obtained From Various Frequency Distributions for the July and August Total Monthly Flows in $dam^3\ month^{-1}$, 1966-1983.

Month	Return Period Year	Probability %	DISTRIBUTIONS GEV	3-PLN	LP-III	Wakeby
JULY	1.003	99.7	2650	2670	2690	954
	1.05	95.2	3210	3190	3210	3220
	1.25	80.0	3700	3680	3700	3720
	2.00	50.0	4290	4280	4280	4180
	5.00	20.0	4970	4990	4970	5020
	10.00	10.0	5360	5420	5380	5590
	20.00	5.0	5700	5810	5750	6120
	50.00	2.0	6090	6280	6200	6750
	100.00	1.0	6340	6610	6520	7190
	200.00	.5	6570	6940	6830	7590
AUGUST	1.003	99.7	2590	2890	3100	2400
	1.05	95.2	3080	3160	3220	2840
	1.25	80.0	3510	3470	3430	3450
	2.00	50.0	4000	3920	3830	3940
	5.00	20.0	4550	4560	4550	4670
	10.00	10.0	4860	5000	5110	5110
	20.00	5.0	5110	5420	5720	5470
	50.00	2.0	5390	5980	6620	5850
	100.00	1.0	5580	6420	7370	6090
	200.00	.5	5740	6860	8220	6280

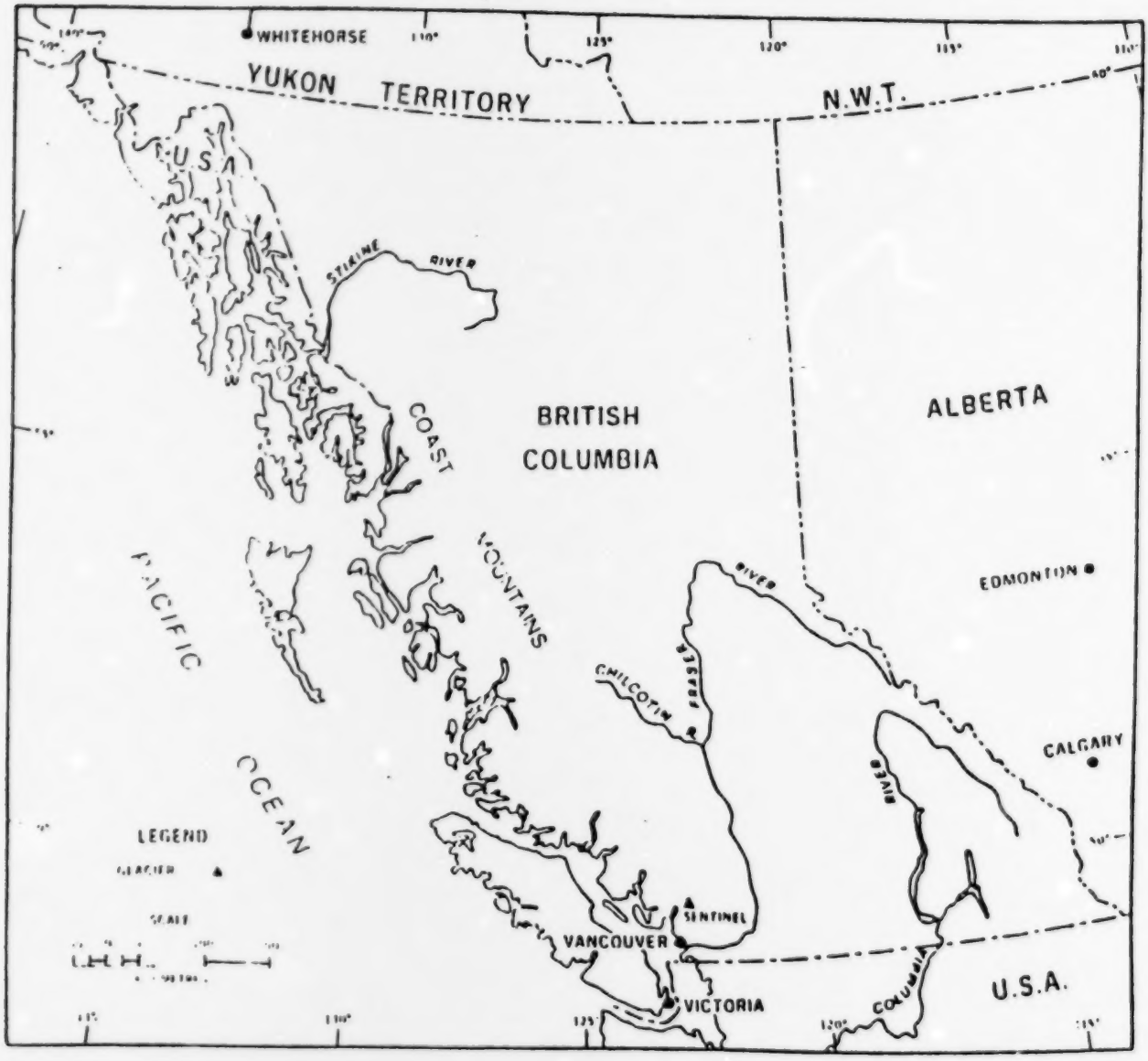

FIGURE 1. LOCATION OF SENTINEL GLACIER

Maximum, minimum and mean total monthly flows from Sentinel Glacier, B.C., May – October, 1966 – 1983

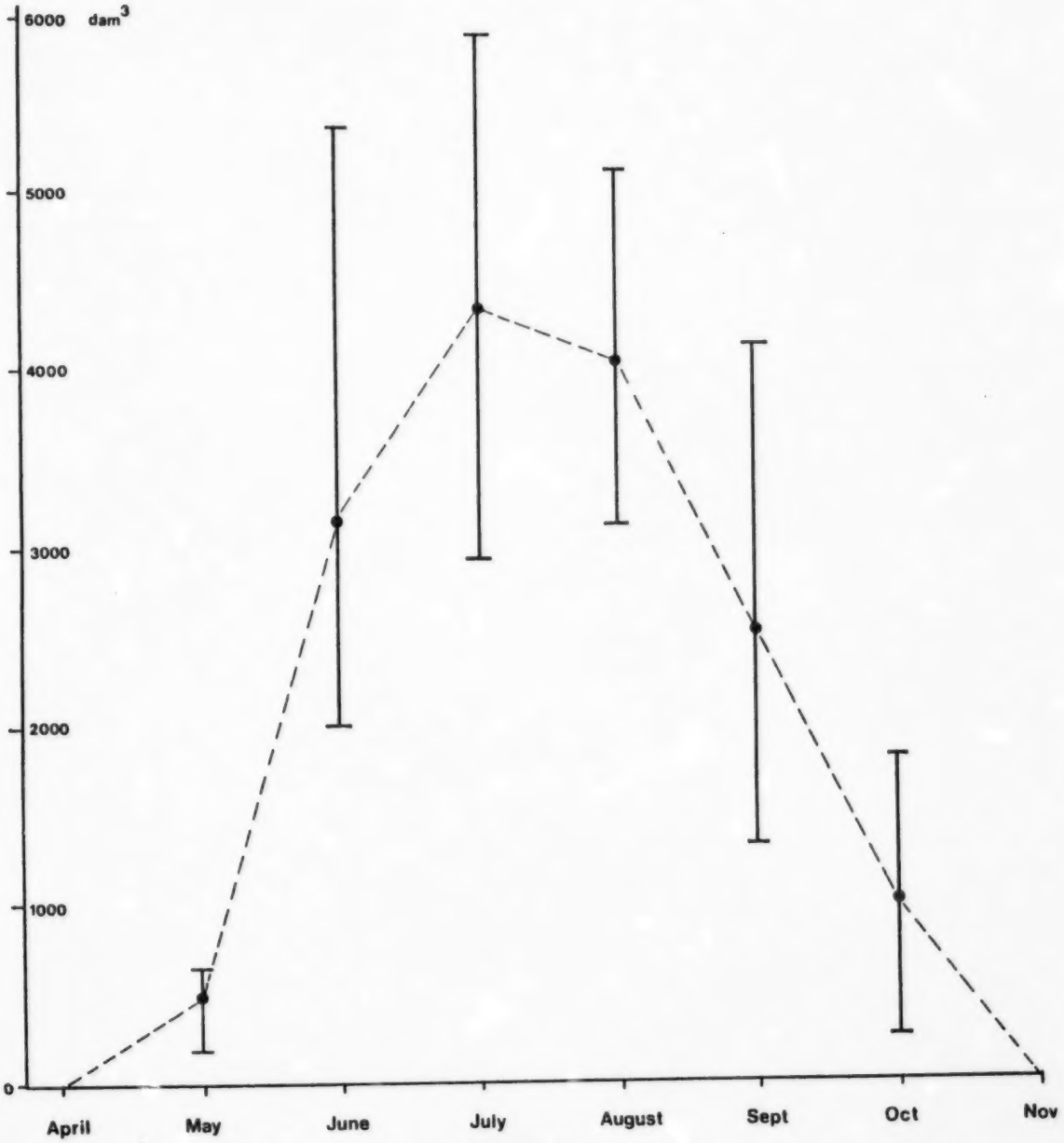

Figure 2

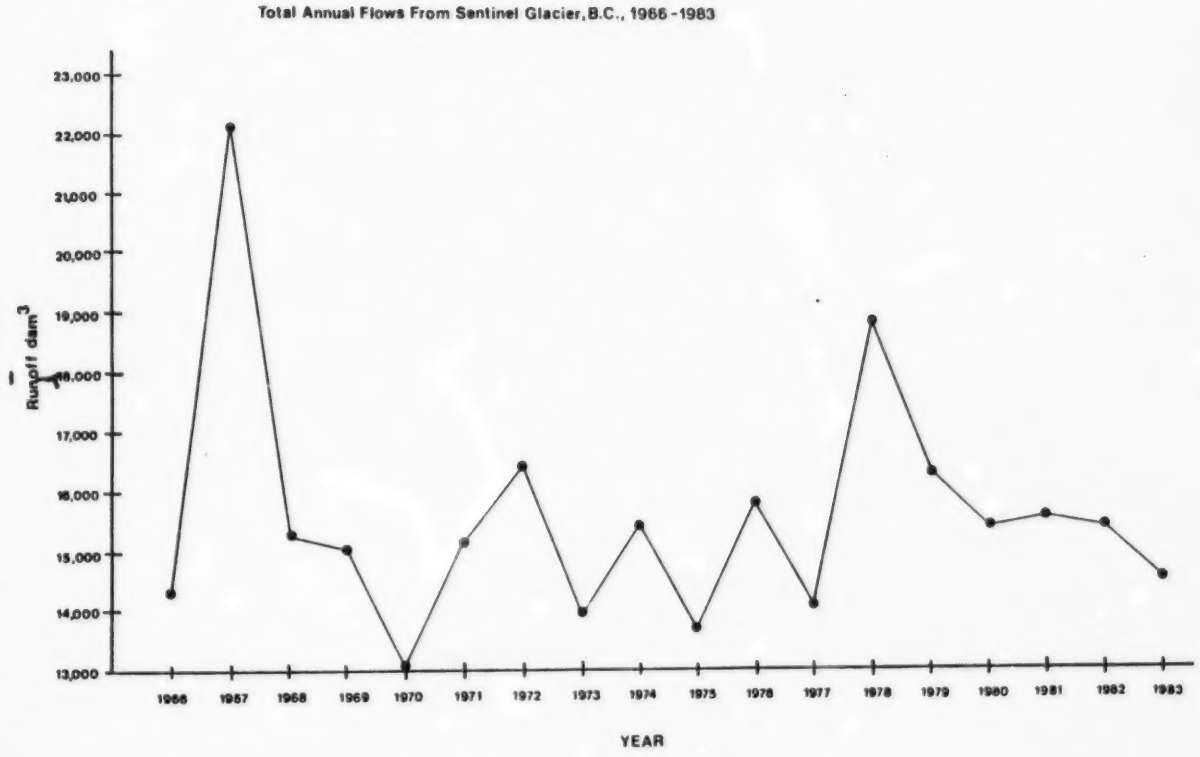
Total Annual Flows From Sentinel Glacier, B.C., 1966 - 1983
Runoff dam^3
23,000
22,000
21,000
20,000
19,000
18,000
17,000
16,000
15,000
14,000
13,000
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
YEAR

Figure 3

Percentage Contribution Of Each Month To The Total Annual Flows, Sentinel Glacier, B.C.
May–October, 1966–1983.

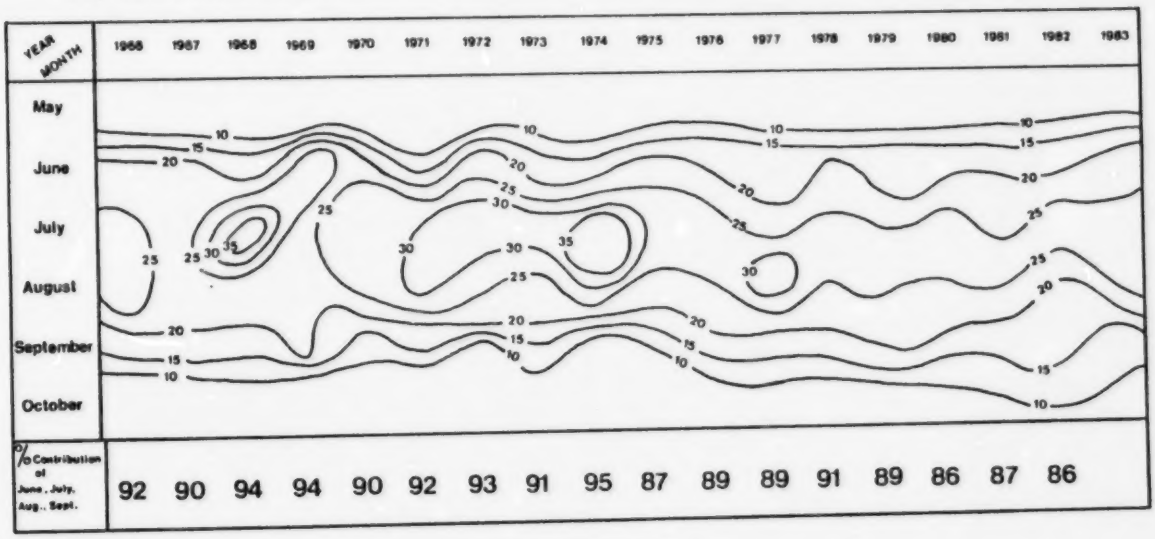

Figure 4

LOGNORMAL PLOTTING POSITIONS OF THE ANNUAL MAXIMA OF DAILY FLOWS, 1966 - 1983

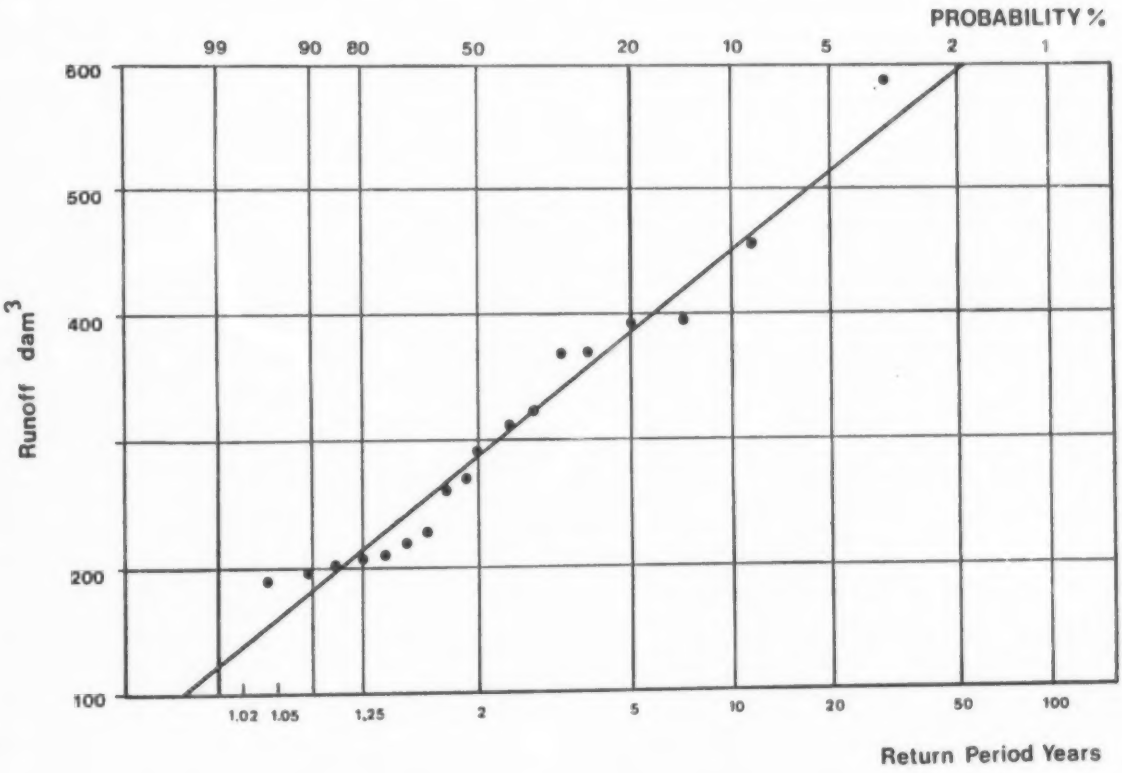

Figure 5

GENERALIZED EXTREME VALUE DISTRIBUTION OF THE ANNUAL MAXIMA OF DAILY FLOWS, 1966-1983

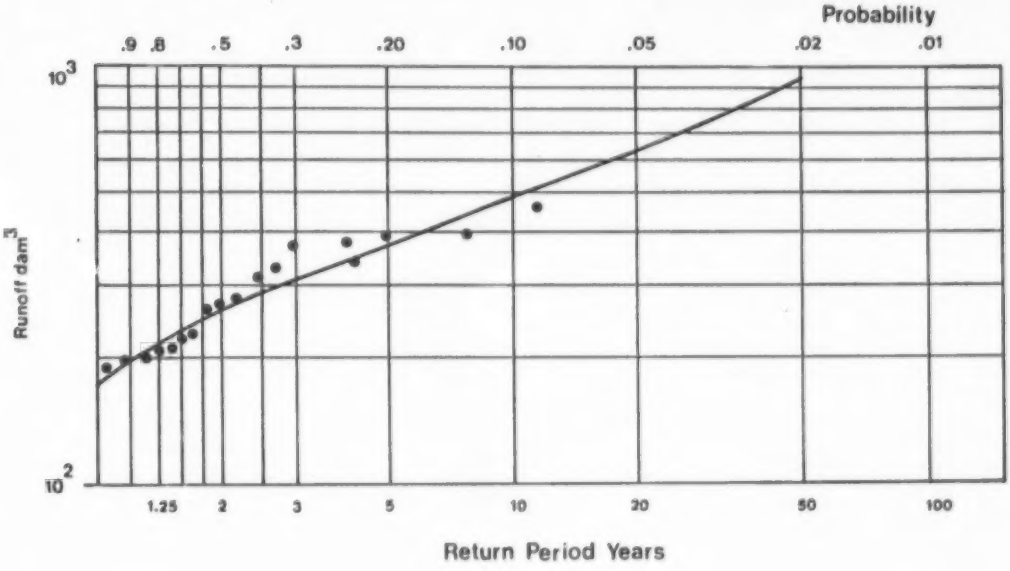

Figure 6

THREE-PARAMETER LOGNORMAL DISTRIBUTION OF THE ANNUAL MAXIMA OF DAILY FLOWS, 1966-1983

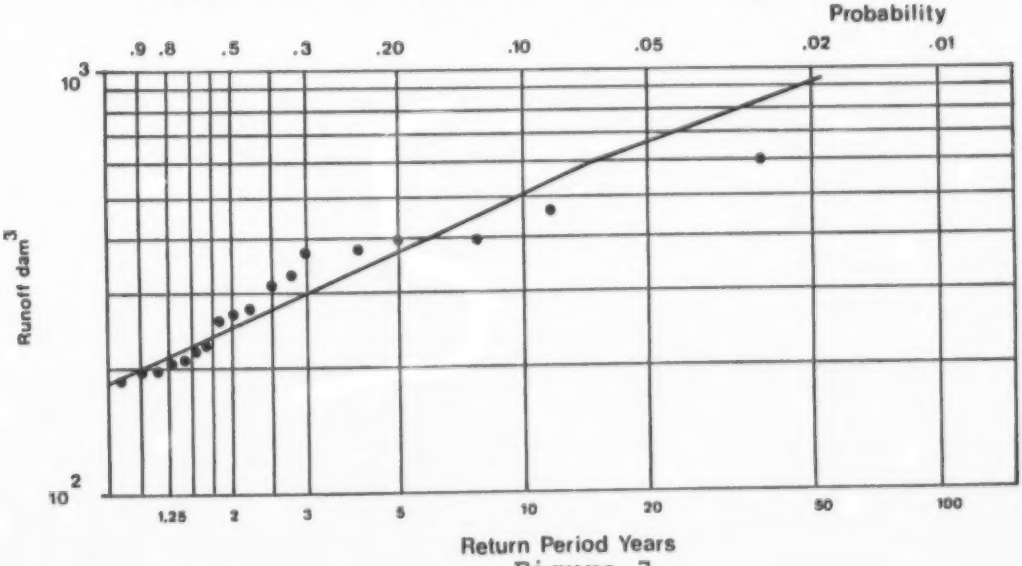

Figure 7

Log Pearson-Type III Distribution of the Annual Maxima of Daily Flows, 1966-1983.

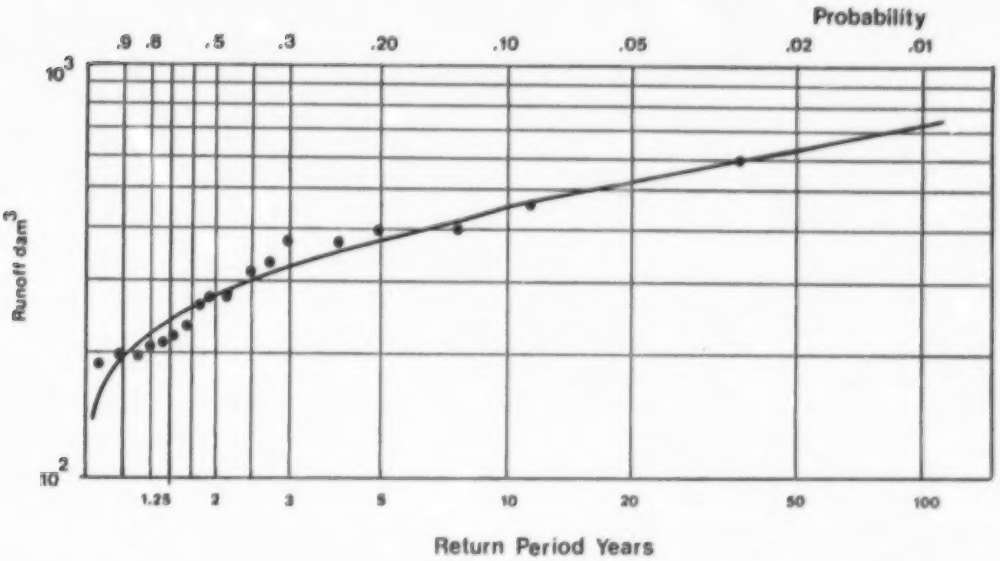

Figure 8

Wakeby Distribution of the Annual Maxima of Daily Flows, 1966-1983.

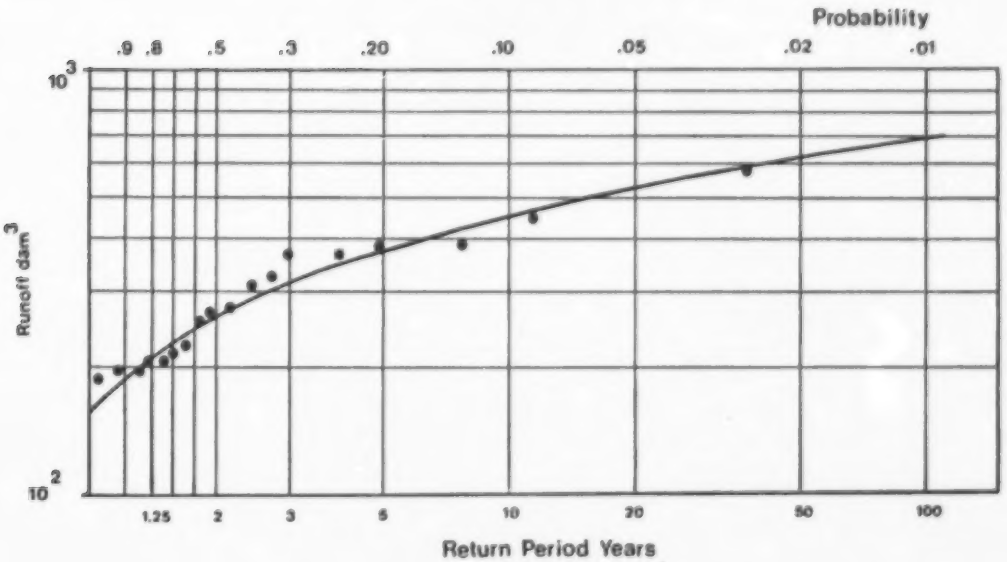

Figure 9

LOG NORMAL PLOTTING POSITIONS OF THE
TOTAL JULY FLOWS, 1966 – 1983

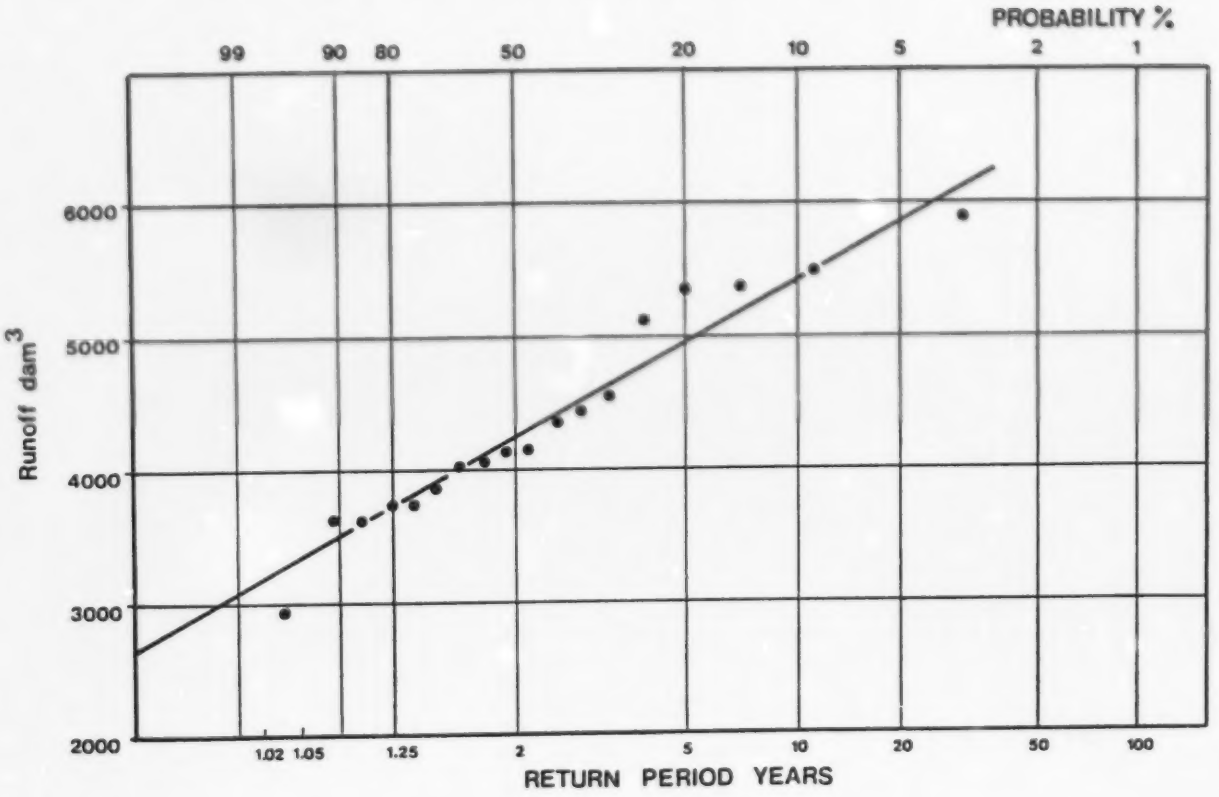

Figure 10

GENERALIZED EXTREME VALUE DISTRIBUTION OF THE TOTAL JULY FLOWS , 1966-1983

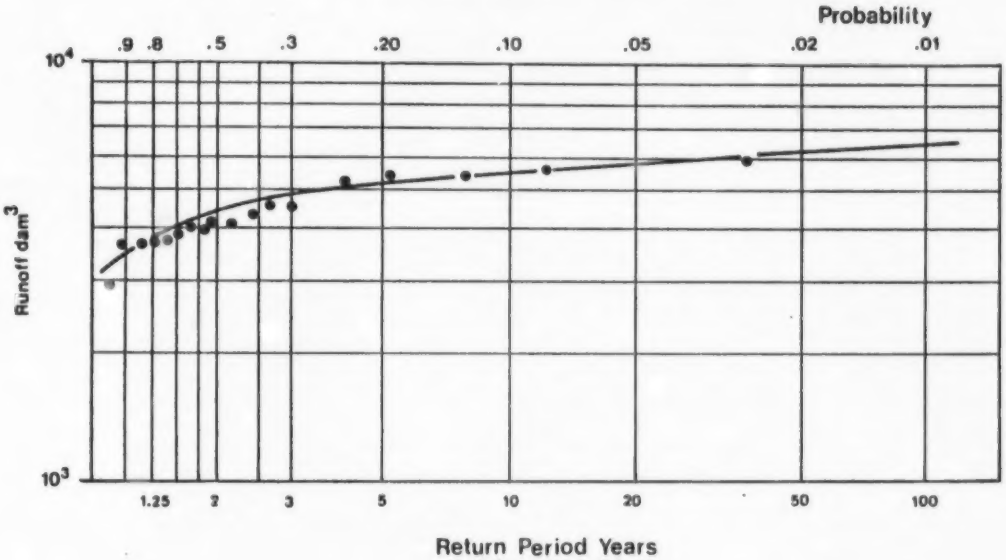

Figure 11

THREE-PARAMETER LOGNORMAL DISTRIBUTION OF THE TOTAL JULY FLOWS ,1966-1983

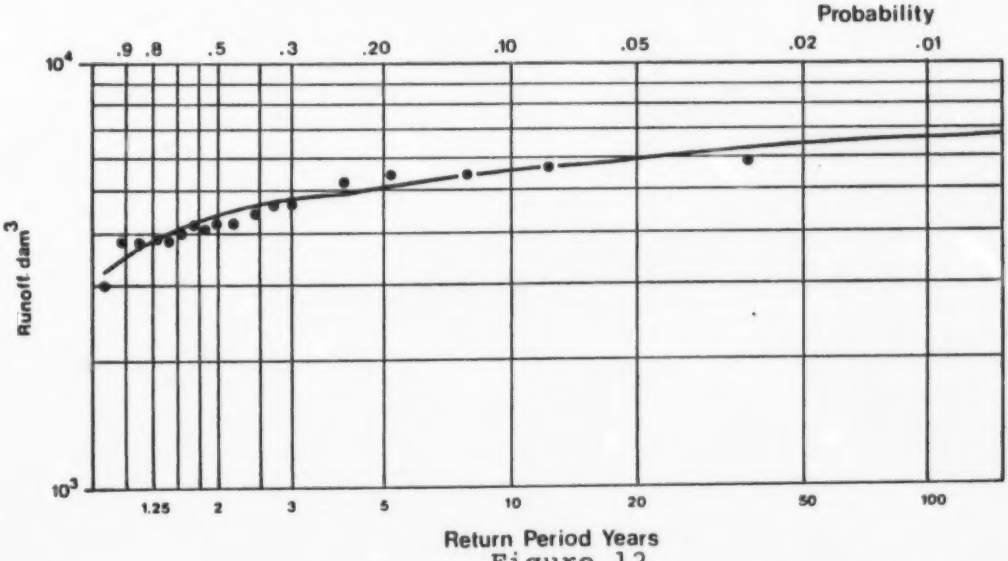

Figure 12

LOG PEARSON TYPE III DISTRIBUTION OF THE TOTAL JULY FLOWS, 1966-1983

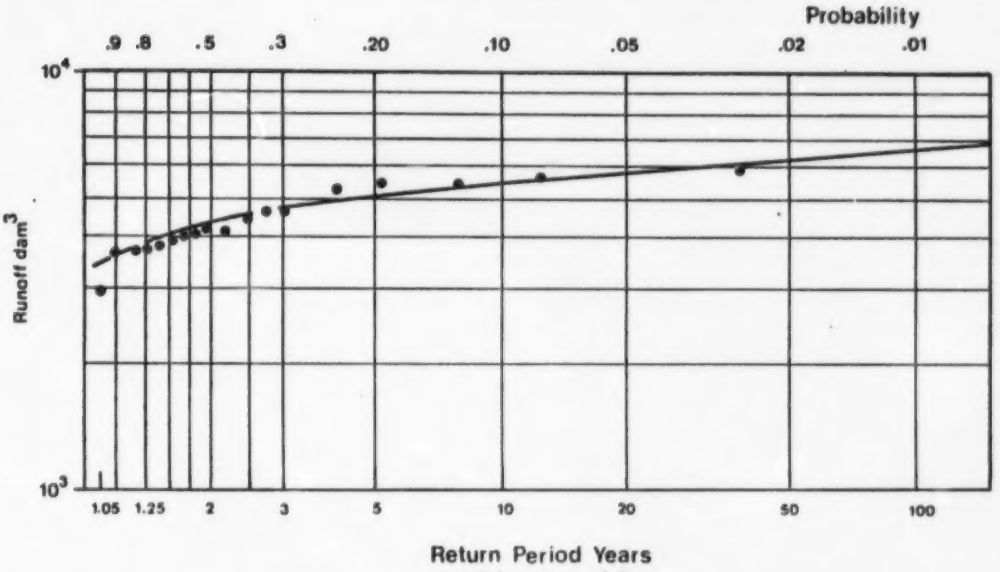

Figure 13

WAKEBY DISTRIBUTION OF THE TOTAL JULY FLOWS, 1966-1983

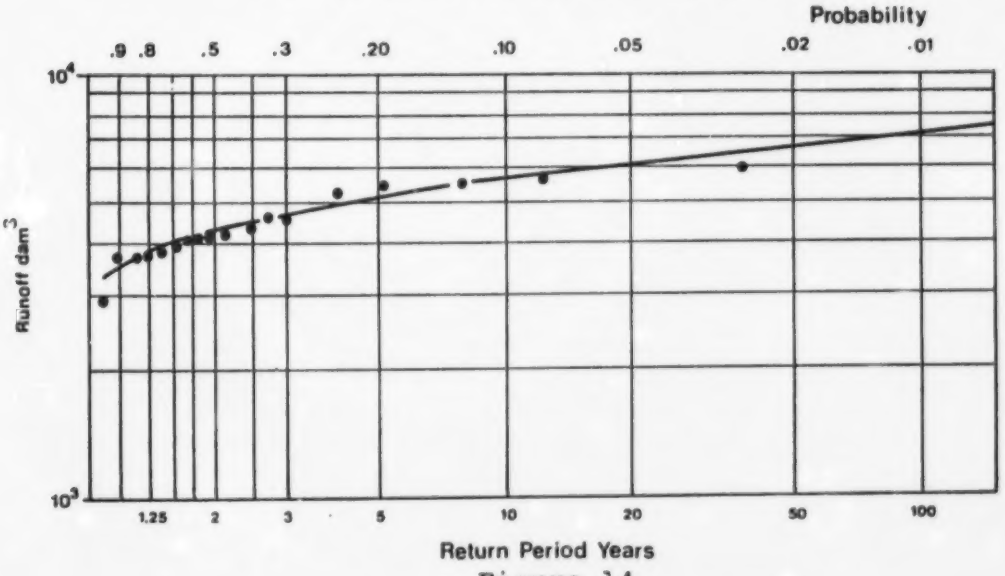

Figure 14

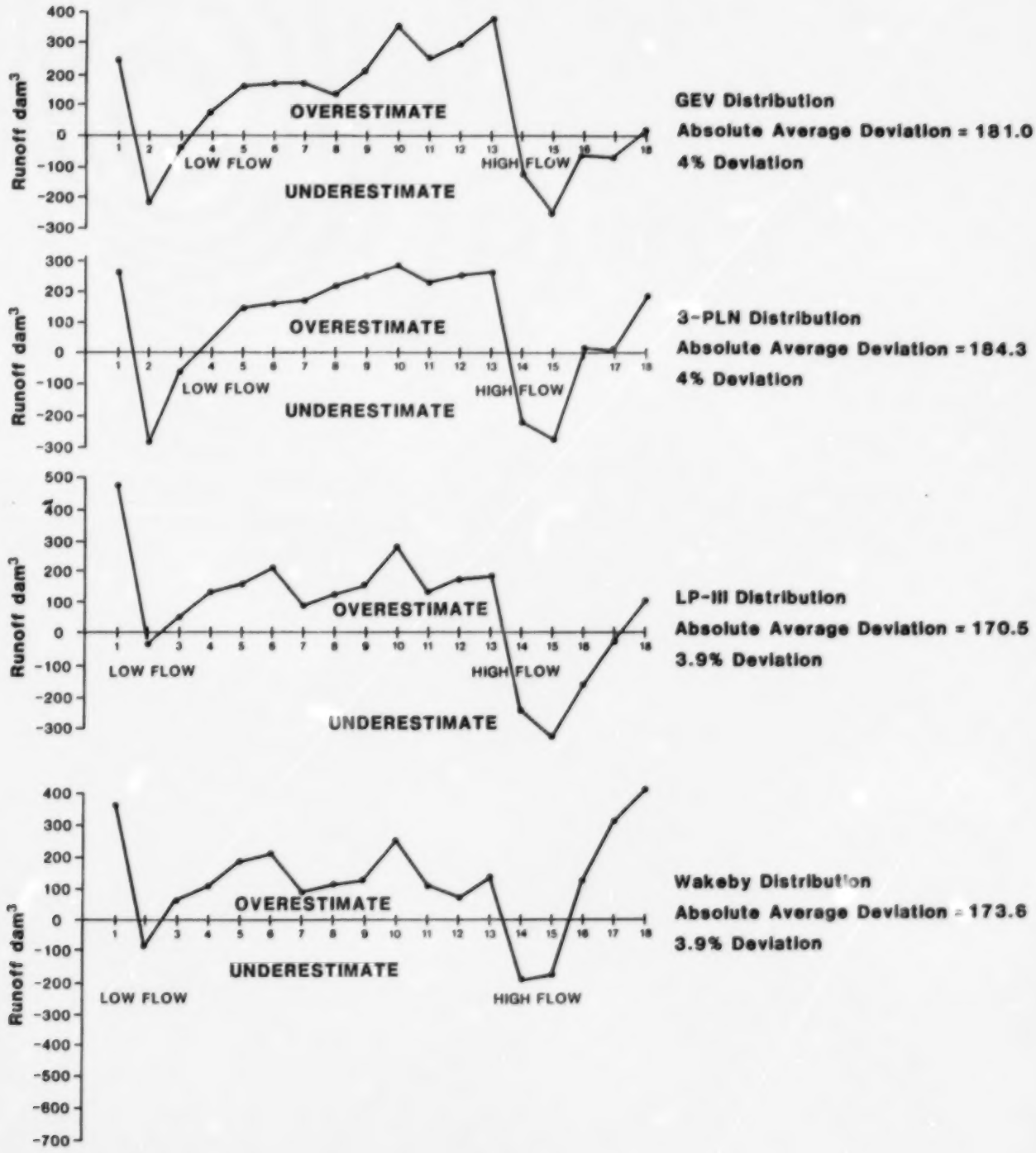

Figure 15. Deviations of the Estimated Flows from Actual Values of the Total July Flows, 1966-1983.

LOGNORMAL PLOTTING POSITIONS OF THE
TOTAL AUGUST FLOWS, 1966-1983

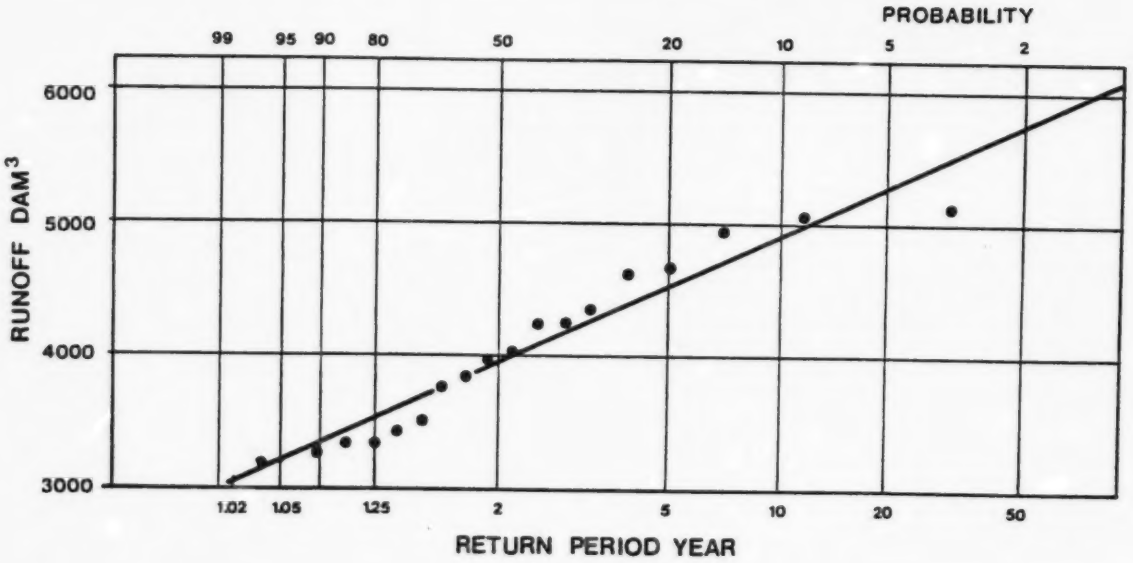

Figure 16

GENERALIZED EXTREME VALUE DISTRIBUTION OF THE TOTAL AUGUST FLOWS, 1966-1983

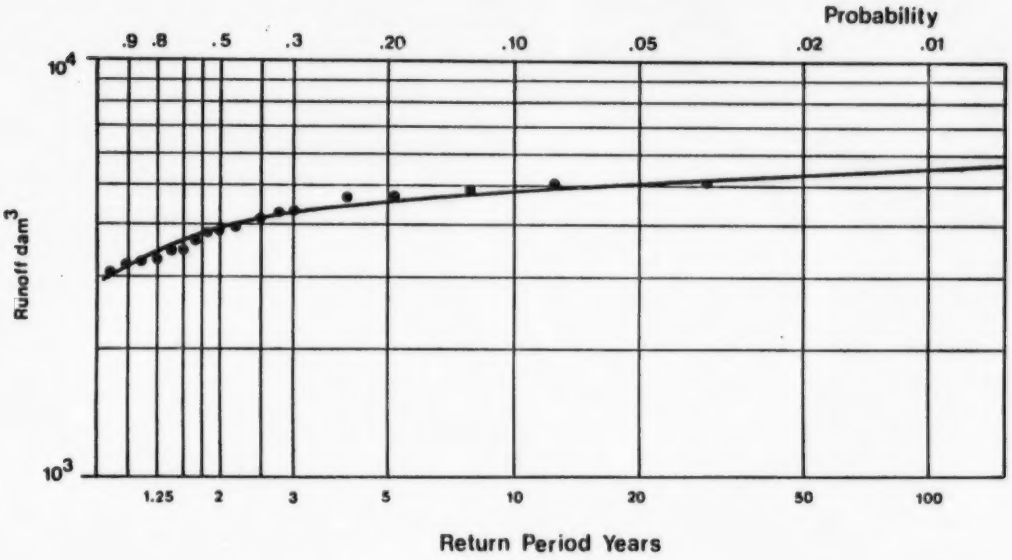

Figure 17

THREE-PARAMETER LOGNORMAL DISTRIBUTION OF THE TOTAL AUGUST FLOWS, 1966-1983

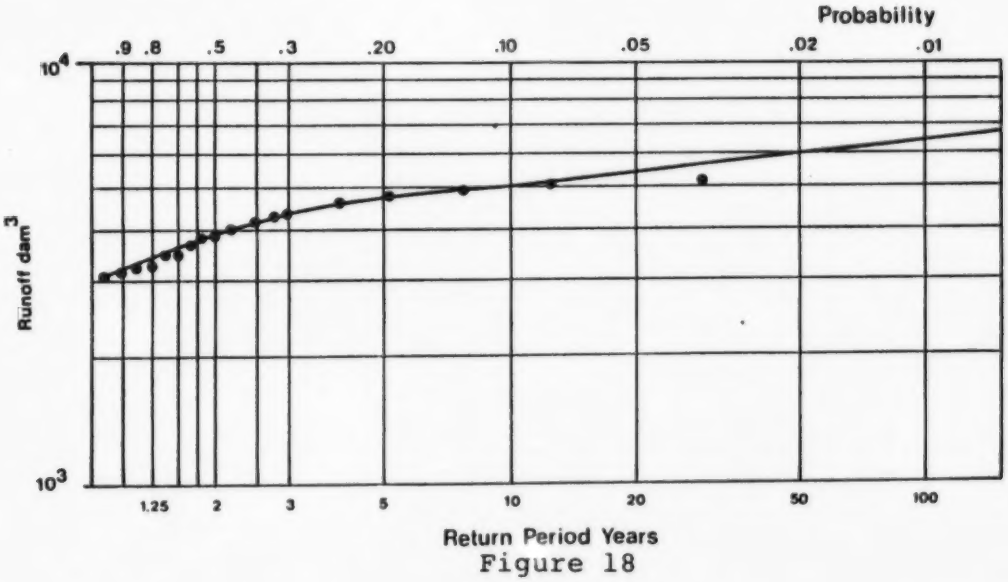

Figure 18

LOG PEARSON TYPE III DISTRIBUTION OF THE TOTAL AUGUST FLOWS,1966-1983

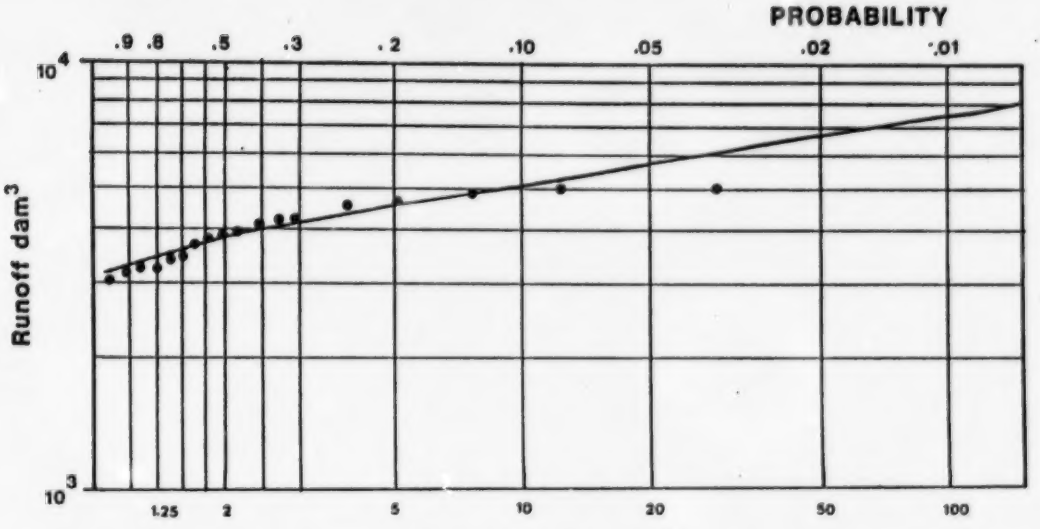

Figure 19

WAKEBY DISTRIBUTION OF THE TOTAL AUGUST FLOWS, 1966-1983

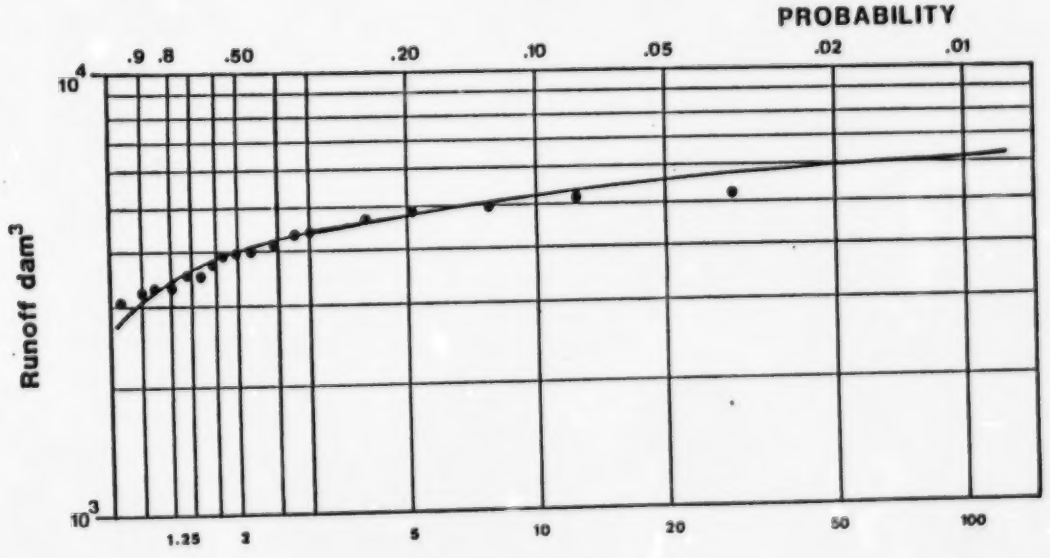

Figure 20

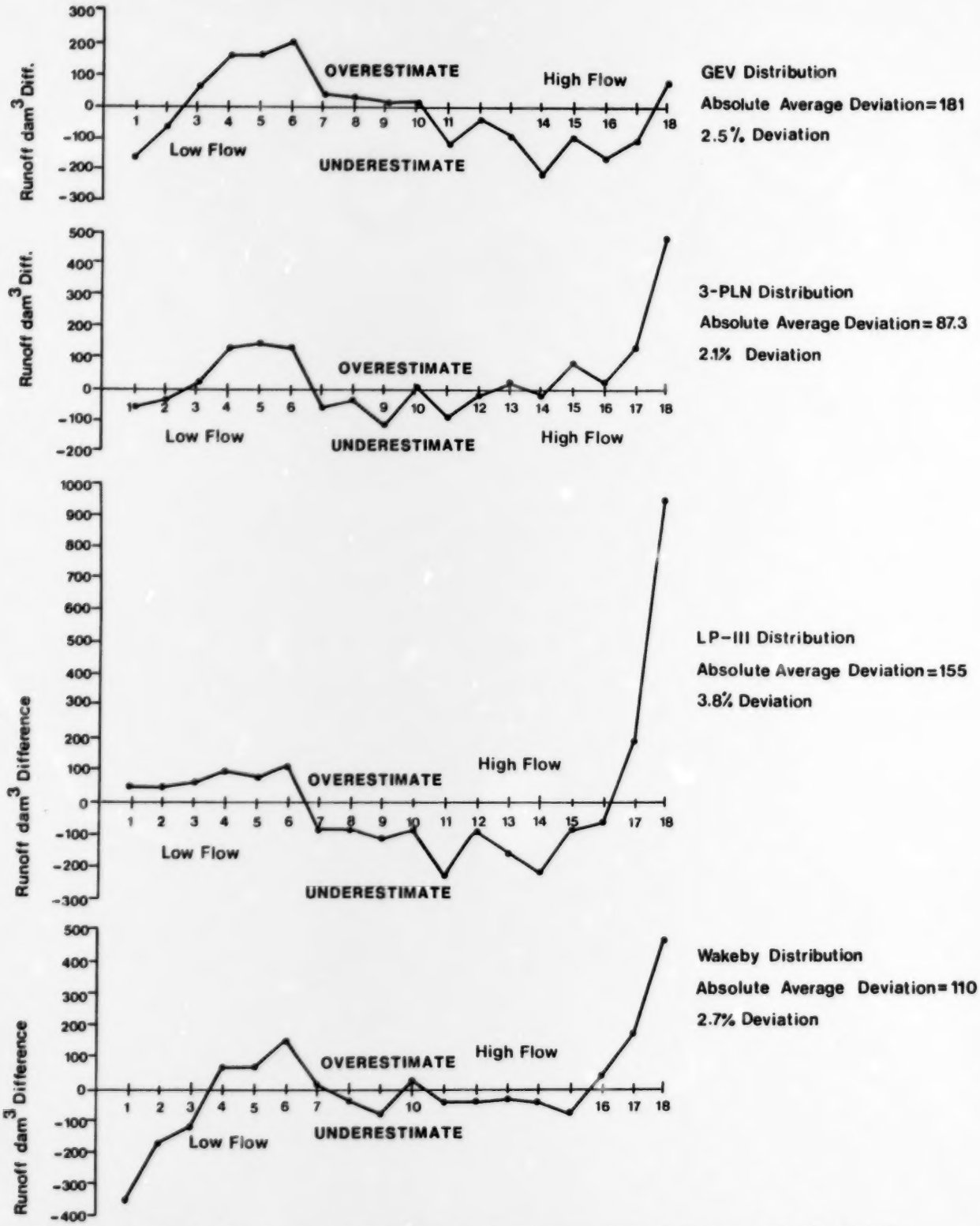

Figure 21. Deviations of the Estimated Flows from Actual Values of the Total August Flows, 1966-1983.